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Colorimetric errors due to a non-linear transfer characteristic and inaccurate gamma tracking

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(PH-69)

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Summary

Gamma-correction of video signals is carried out to counteract the non-linearity in the television display tube. It is well known that the display tube characteristic follows a true power law closely, and if the laws of the camera gamma-correctors are not the true inverse of the tube characteristic, colour errors are to be expected. At present the gamma-corrector law is not a true power law nor is it precisely the inverse of the display-tube law. The resulting colour errors are discussed and may well be the cause of some common criticisms of colour television pictures.

1. Introduction

Cathode-ray display-tubes have a power law characteristic above cutoff, below which there is no beam current and no light output. Following the notation of Bingley,[1] the characteristic can be represented by

$$T_2 = a[(E_0 - E_c) + E]^{\gamma_2} \tag{1}$$

where T_2 is the light output of the tube in any consistent unit;*

E_c is the cutoff voltage;

E_0 is the bias voltage added to the signal;

E is the signal voltage;

a and γ_2 are constants*

Suppose the camera transfer characteristic is represented by the equation

$$E = c + bT_1^{\gamma_1} \tag{2}$$

where c is a 'sit' voltage;

b is a constant relating tristimulus value to voltage;

γ_1 is a constant, not necessarily the reciprocal of γ_2;*

T_1 is the light input to the camera tube.*

The overall characteristic is determined by combining Equations (1) and (2) to give

$$T_2 = a[(E_0 - E_c) + c + bT_1^{\gamma_1}]^{\gamma_2}$$
$$= a[(E_0 - E_c + c) + bT_1^{\gamma_1}]^{\gamma_2} \tag{3}$$

* The subscripts 1 and 2 are used to denote that the terms involved refer to the camera and display respectively.

The 'sit' voltage has been absorbed in the cutoff and bias voltages of the display tube. The first step towards accurate reproduction is to adjust either the 'sit' voltage, c, or the bias voltage, E_0, so that the sum $(E_0 - E_c + c)$ vanishes. The transfer equation then becomes

$$T_2 = ab^{\gamma_2} T_1^{\gamma_1 \gamma_2} \tag{4}$$

To obtain precise reproduction of luminance and chromaticity, two further steps are necessary, and are given by the equations

$$ab^{\gamma_2} = 1 \tag{5}$$

and

$$\gamma_1 \gamma_2 = 1 \tag{6}$$

In practice, no attempt is made to satisfy Equation (5) because the luminance of the original scene is very often much higher than that of any display monitor and considerations of flicker and glare would make identity of reproduced and original luminances highly undesirable even if it were technically possible. What is aimed at is proportionality of the corresponding luminances of picture elements in the original and reproduced scenes. If the gamma-correctors at the sending and receiving ends are not the inverse of each other, errors of reproduction are produced. In a black-and-white television system, these errors manifest themselves as differences in tonal graduation. In a colour television system, however, both luminance and colour errors are produced. In this report the magnitude and direction of the errors in colour are determined, assuming both true power laws in the gamma-correctors and the gamma characteristics of a typical four-tube colour-camera.

2. Gamma-correctors having a pure power law

Modern colour television display tubes have an average gamma of between 2·7 and 2·8, depending upon whether they are cathode- or grid-modulated; measurements have

shown that, over the great majority of the operating range, the characteristics can be represented very accurately by a true power law. Camera gamma correctors, on the other hand, only approximate to a power law and, partly because of noise considerations, this law has an index of 1/2·2. Thus the overall transfer characteristic approximates to a power law of index 2·8/2·2 (i.e. 1·27). The overall characteristic is thus non-linear at least to the extent shown in Fig. 1.

A computer programme was used to calculate the colorimetric performance of the television system, the figure of 1/2·2 being assumed for the camera gamma-corrector and 2·8 for the display-tube characteristic. The chromaticity diagram of Fig. 2 shows the results of this calculation and indicates the chromaticity errors which arise due to the non-linear overall characteristic. In all the results quoted here, the camera assumed was a typical four-tube camera using standard Plumbicon tubes and a 3 x 3 matrix in the colouring channels: it was assumed to operate in a studio illuminant of 3000°K. The test colours for these camera performance check programmes were those used in all recent BBC theoretical work and consist of eight saturated colours, eight desaturated colours, eight skin tones and two grasses.[2]

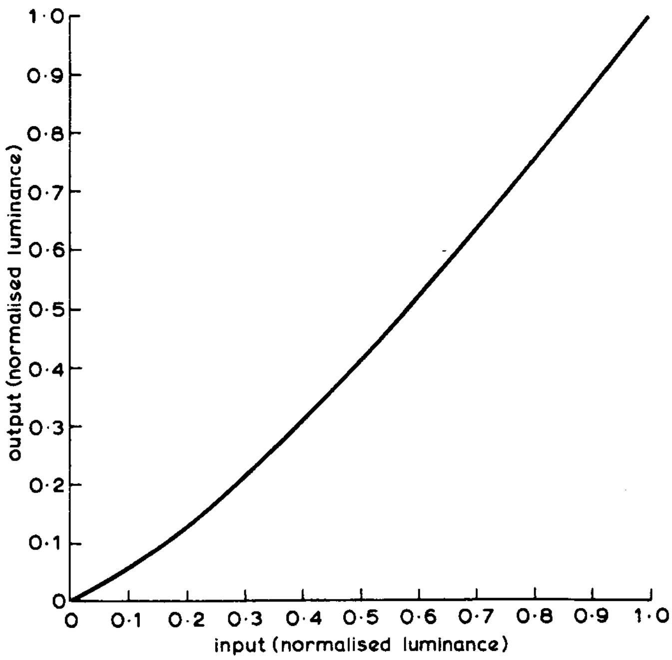

Fig. 1 - Transfer characteristic of television system
γ = 1·273

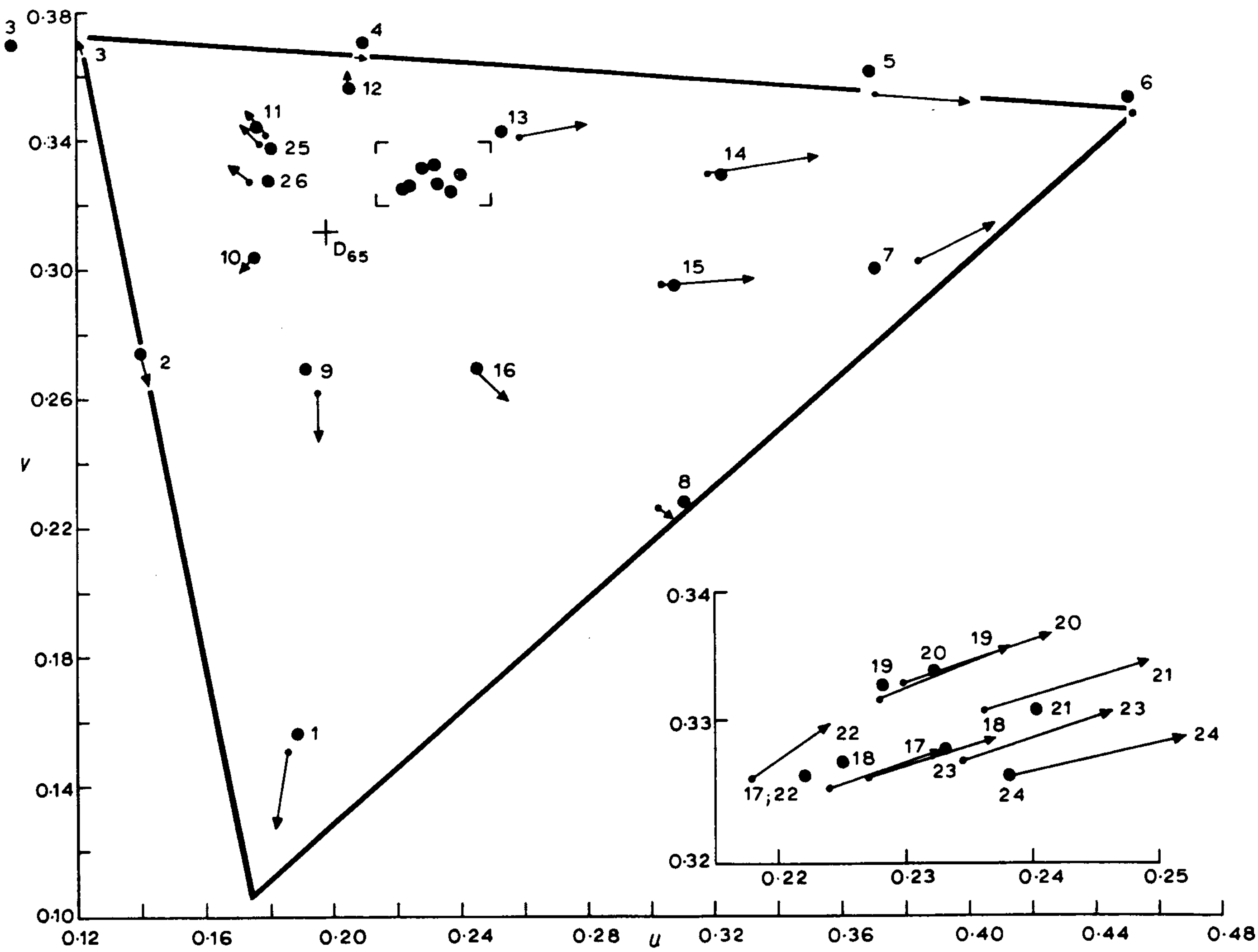

Fig. 2 - Chromaticity shifts caused by a transfer gamma of 1·273 (typical 4-tube camera)

Base of arrow: chromaticity for a linear system;
Head of arrow: chromaticity for a non-linear system

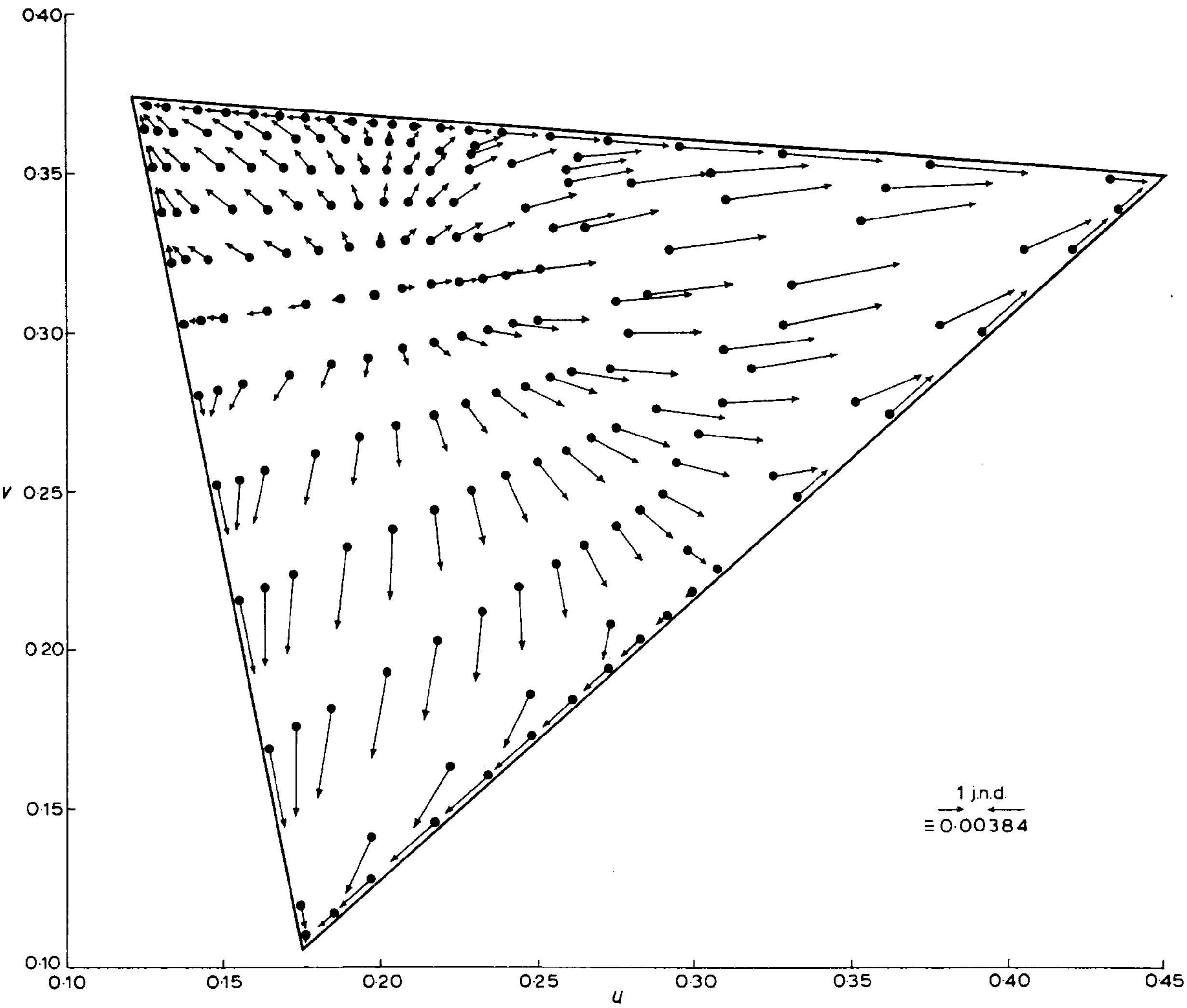

Fig. 3 - Chromaticity shifts caused by a transfer gamma 1·273 ('perfect system')

Base of arrow: chromaticity for a linear system;
Head of arrow: chromaticity for a non-linear system

The colour errors are far from negligible and in some cases add to smaller errors that occur due to non-perfect camera analysis for the condition of an overall unity-gamma transfer characteristic. Nevertheless, reproduction with an overall gamma of 1·273 is judged to be very good by experienced observers. There is thus an apparent contradiction between the results of colorimetric calculations and practical observations; however, all the optimum requirements for the reproduction of colour television pictures are not known. There is some evidence[3] that an overall gamma of a little over unity is preferred.

Data of the type given in Fig. 2 shows the objective accuracy (or otherwise) of a specified colour television chain of equipment including a camera and a display monitor.

The objective effect of using an overall gamma of 1·273, in an otherwise 'perfect' system, for a grid of chromaticities covering the whole of the RGB triangle given by a set of modern phosphors is shown in Fig. 3. In general, it will be seen that both hue and saturation are altered: saturation is always increased, except for colours already having the maximum possible saturation and hue is changed in the direction of the dominant primary colour. Luminance is also distorted although Fig. 3 does not show this. For the chromaticities on the red-cyan, green-magenta and blue-yellow axes hue is unchanged. White is also unchanged.

3. Gamma-correctors having a non-ideal characteristic

Practical gamma correctors having measured characteristics not following a pure power must now be considered; errors of the same general nature are produced, and it is the differences between the errors of practical and of pure power-law gamma correctors which are of particular

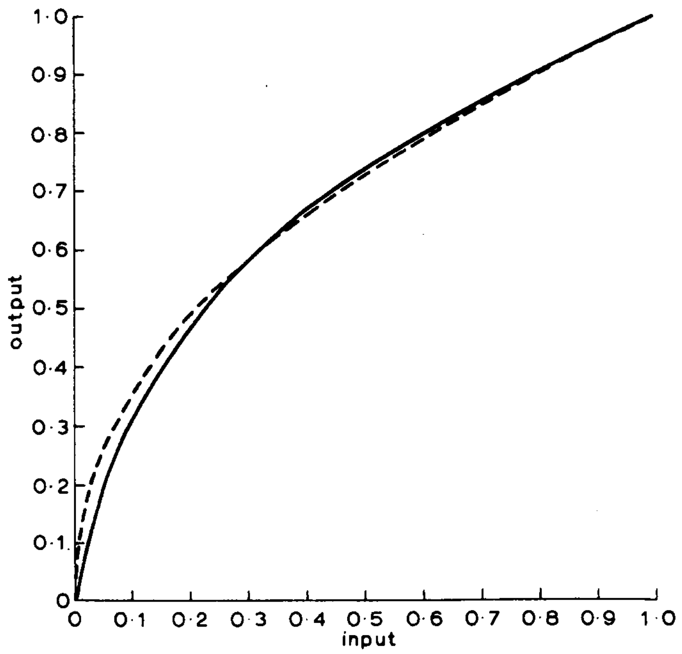

Fig. 4 - Gamma-corrector characteristic

—— measured curve

– – – true power law, $\gamma = 1/2{\cdot}2$

interest. Fig. 4 shows how the actual curve of one gamma-corrector differs from a pure power law of exponent 1/2·2. In the typical four-tube colour camera which is being considered, there are five gamma-correctors, one in each of the three colouring channels and one each in the wide- and narrow-band luminance channels. The computer programme was modified in such a way that it could take five individual curves for gamma-correction and, in order to make a study of the errors produced by the gamma-correctors alone (and not those produced by the transfer gamma of 1·273), the gamma of the display tube for this particular investigation was taken to be 2·2. In this way, any departure from the colorimetric performance of an ideal linear system must be because the gamma-correctors do not follow a true power-law curve. Putting the practical curve of Fig. 4 into all the 'gamma-correctors' of the computer programme gives the results plotted in Fig. 5.

Even though Fig. 5 is representative only of the errors occurring in 26 particular cases, it shows the form of errors that can be expected from non-ideal gamma-correction; in general, low luminance colours will suffer the greater errors owing to the fact that they will give rise to signals which explore the more erroneous regions of the gamma characteristics. In practice, low-luminance colours are found in

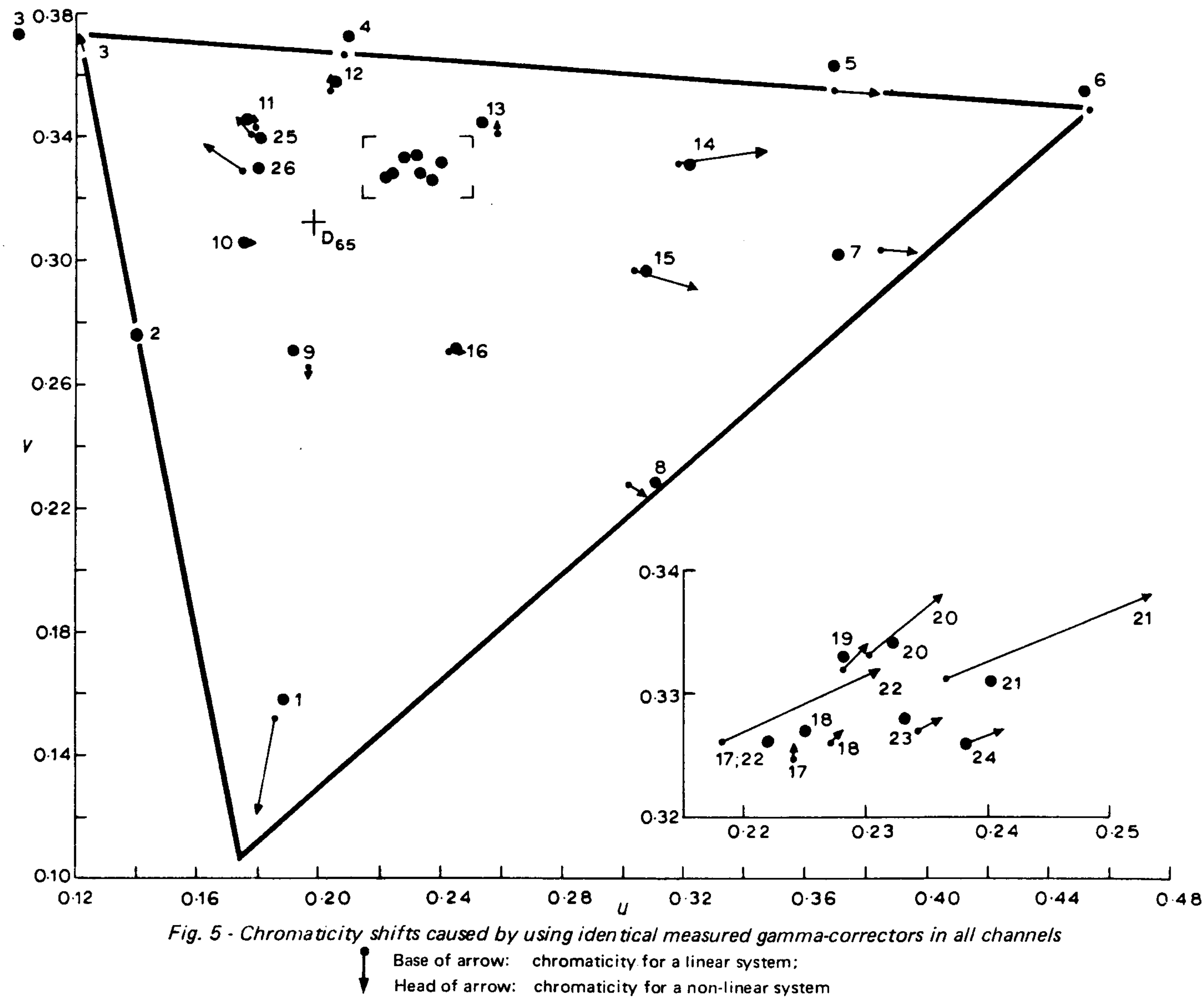

Fig. 5 - Chromaticity shifts caused by using identical measured gamma-correctors in all channels

Base of arrow: chromaticity for a linear system;

Head of arrow: chromaticity for a non-linear system

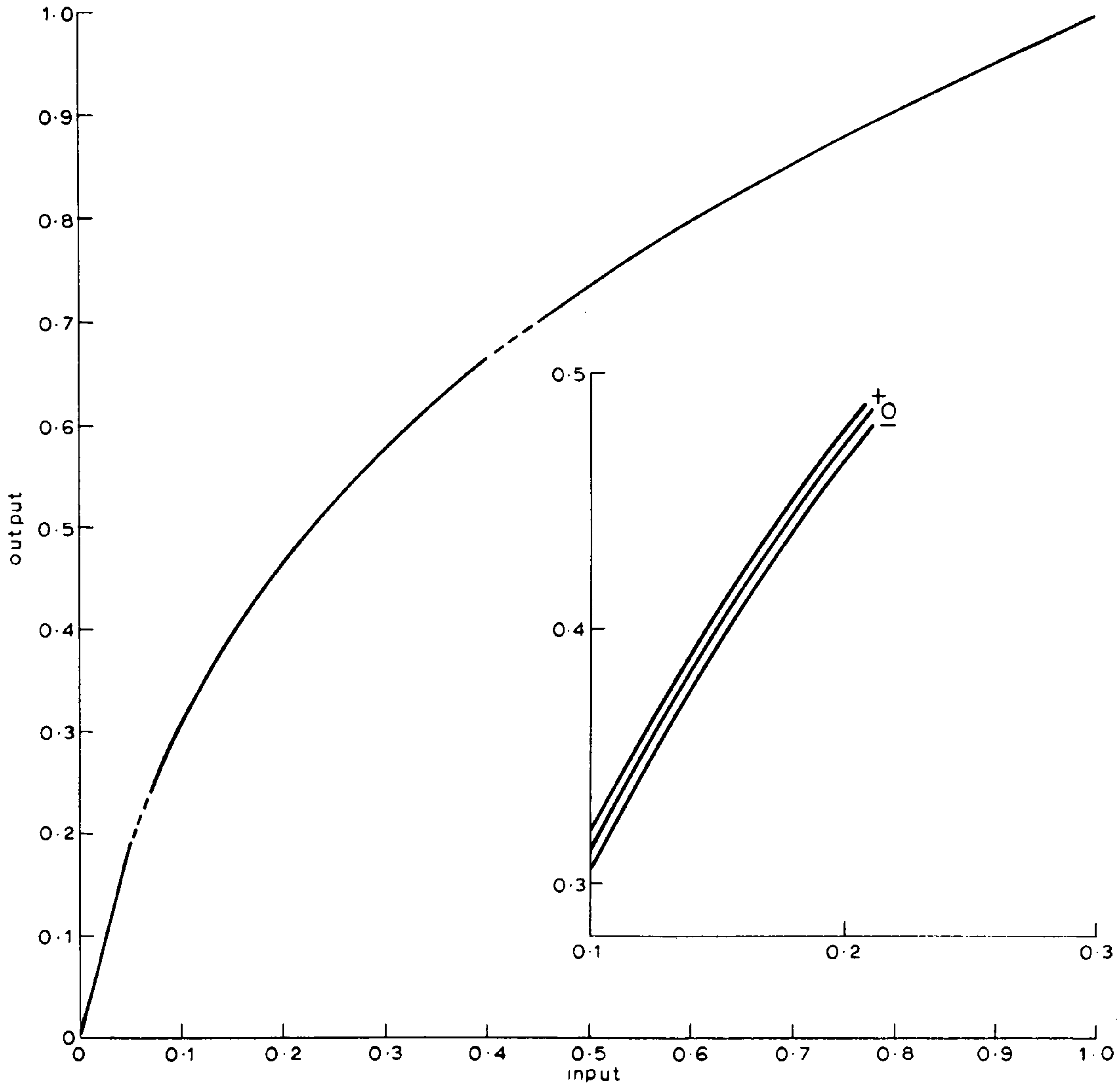

Fig. 6 - Curves used in the differential gamma error calculations
Inset diagram shows the three individual curves on an enlarged scale

the shadows of an otherwise highly-illuminated scene and good reproduction in shadows can therefore only be produced by more accurate gamma-correction at low signal levels.

Since colour reproduction is sensitive to errors in gamma-correction, the matching of gamma-correctors in a camera is clearly vital if good, consistent colour fidelity is to be obtained.

Fig. 5 has shown the results to be expected from perfectly matched, but not 'true power-law' characteristics. However, suppose that there is some mismatch of the gamma curves in the colouring channels — what effect will this have on the colour fidelity? For simplicity it will be assumed that the two luminance-signal gamma-correctors of the camera are matched. For the colouring channel gamma correctors the measured curve of Fig. 4 has been taken as standard and small positive and negative errors superimposed upon it to simulate different types of mismatch. The resulting curves are shown in Fig. 6; they are identical above 45% input, a reasonable assumption because in practice, there is no difficulty in matching the curve over this range. The magnitude of the errors introduced below 45% was chosen to represent errors just detectable on a typical waveform monitor having a trace area about 6 cm x 4 cm and a well-focussed electron beam. Denoting the curves of Fig. 6 by the subscripts +, 0, – for the curves having positive, zero and negative errors respectively, and the three gamma-correctors by $R\,G\,B$ then there are 27 possible arrangements. The effects of all these cases have been computed; 18 show a marked trend and the remaining 9 are trivial. The 9 trivial cases fall into two groups (*a*) and (*b*):

Group (*a*)	(i)	R_0	G_0	B_0	(as shown in Fig. 5)
	(ii)	R_+	G_+	B_+	
	(iii)	R_-	G_-	B_-	

The first of these (*a*)(i) is the reference by which the others are judged, and the remainder exhibit slight colorimetric errors of the type described in Section 2. This is to be expected, because the 'matching' is perfect in all three cases and any colorimetric errors for cases (*a*)(ii) and (*a*)(iii) are produced by deviations from (*a*)(i)

<u>Group (*b*)</u>

Group (*b*)	(i)	R_+	G_0	B_0,	R_-	G_0	B_0
	(ii)	R_0	G_+	B_0,	R_0	G_-	B_0
	(iii)	R_0	G_0	B_+,	R_0	G_0	B_-

The errors produced in these cases are negligible, being of the order of 0·2 j.n.d. for each of the test colours used.

The 18 non-trivial cases all showed similar effects and, from these, a representative set of six has been chosen for the purpose of illustrating the types of errors produced. They represent the general case because each of the curves (+, 0, –) is used in turn in each of the gamma-correctors; these six cases are:

Group (*c*)	(i)	R_+	G_-	B_0
	(ii)	R_-	G_+	B_0
	(iii)	R_0	G_+	B_-
	(iv)	R_0	G_-	B_+
	(v)	R_+	G_0	B_-
	(vi)	R_-	G_0	B_+

The results for the first two cases are shown in Fig. 7; the larger dots show the reproduction calculated for identical (measured) gamma correctors with characteristics as shown in Fig. 4 and correspond to the heads of the arrows in Fig. 5. In this way, all the vectors in Fig. 7 are generated as a result of the differential errors in the gamma-correctors. In the main body of the diagram, only three colours are appreciably affected – two by case (*c*)(i) and one by case (*c*)(ii). The skin-tone area (inset) shows some very interesting effects. The errors are almost entirely in the green-magenta directions. It is noteworthy that the low luminance flesh colours (21 and 22) are affected most.

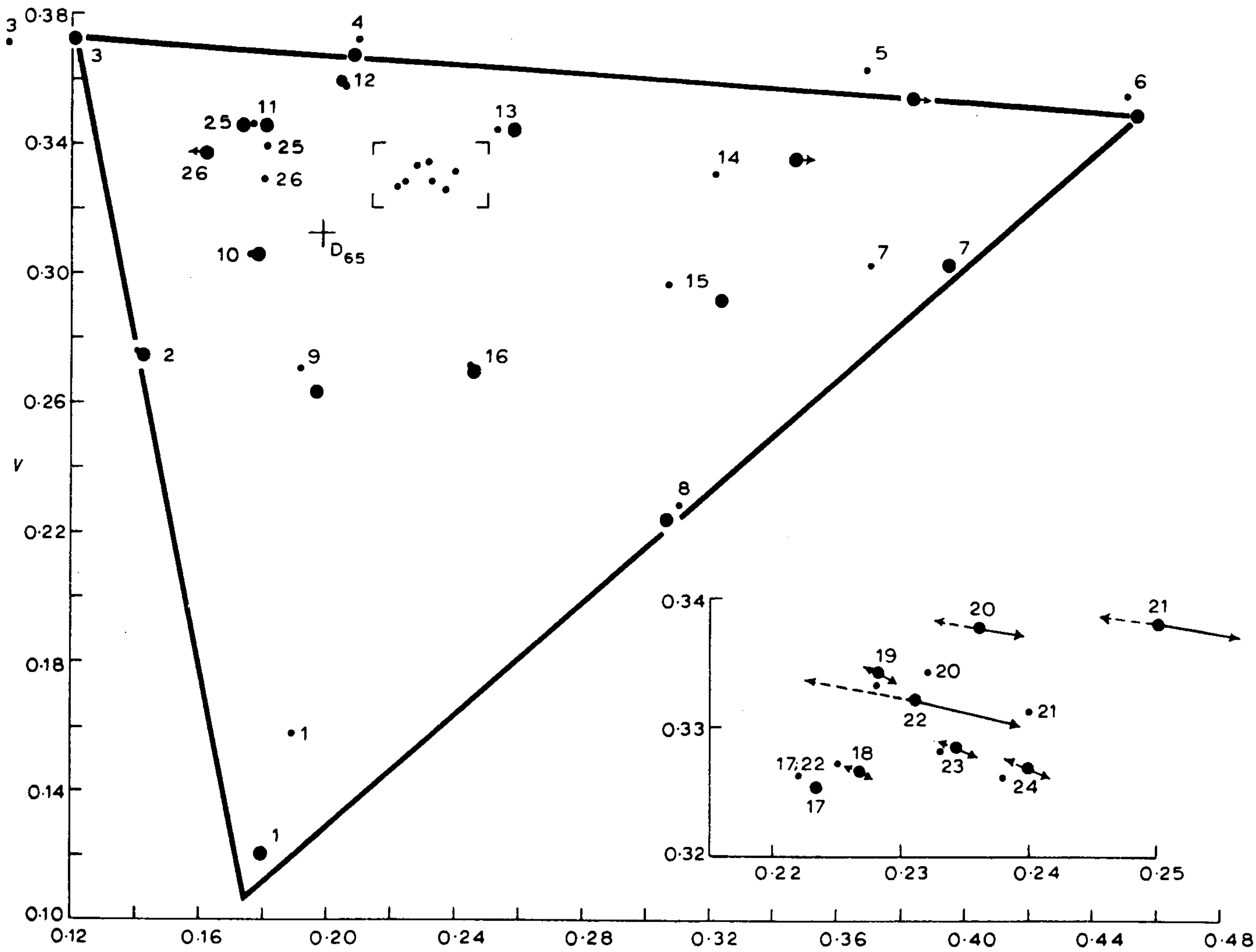

Fig. 7 - Errors caused by differential red/green gamma errors

● Original chromaticity ● Chromaticity with zero mismatch in gamma correctors

——→ $R_+ \; G_- \; B_0$ mismatch – – → $R_- \; G_+ \; B_0$ mismatch

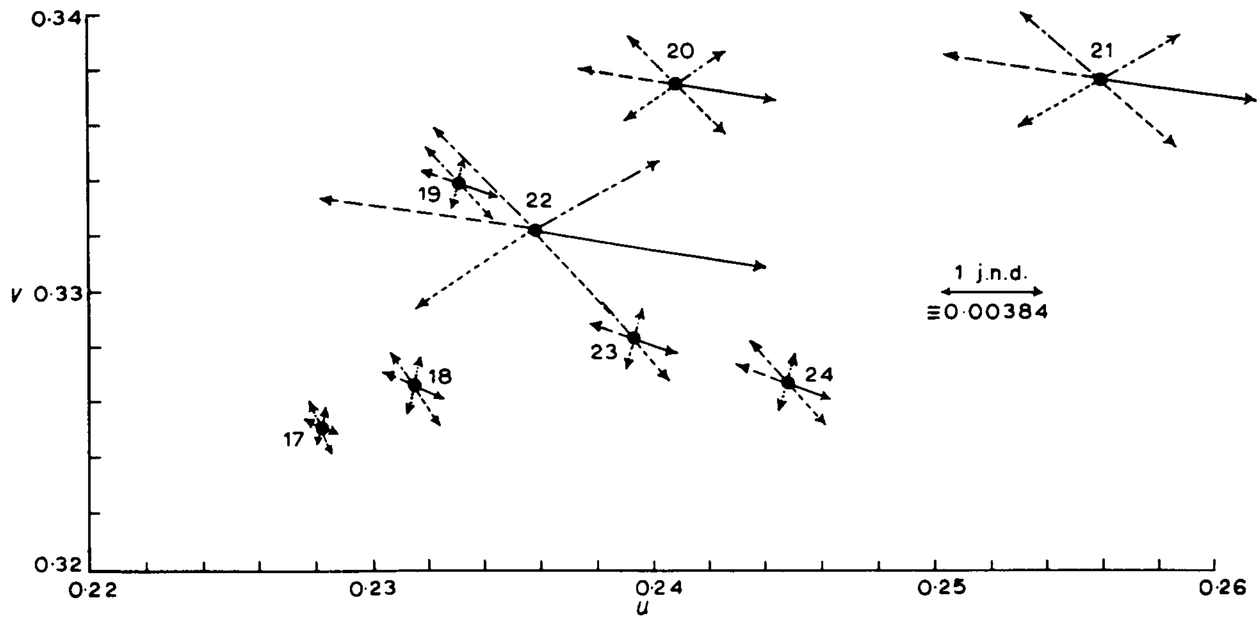

Fig. 8 - Skin tone errors caused by differential gamma-corrector errors

—— R_+ G_- B_0 – – – R_- G_+ B_0 —·—R_0 G_+ B_- -----R_0 G_- B_+ — —R_+ G_0 B_- ····R_- G_0 B_+

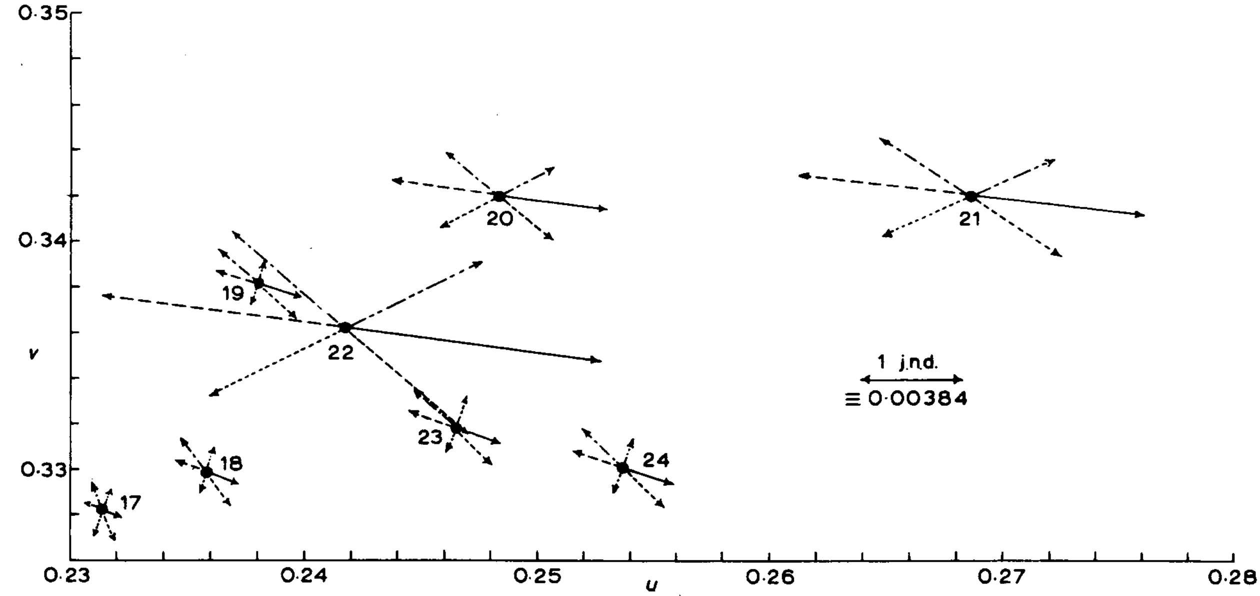

Fig. 9 - Skin tone errors caused by differential gamma-corrector errors

System has an overall transfer gamma of 1·273

—— R_+ G_- B_0 – – – R_- G_+ B_0 —·—R_0 G_+ B_- ----R_0 G_- B_+—··—R_+ G_0 B_- ·····R_- G_0 B_+

The results for the above six cases were calculated and their results over the main portions of the diagram were no more serious than for cases (*c*)(i) and (*c*)(ii) (Fig. 7). Skin tones were most affected; the effect of all six cases on the skin tones is most clearly shown in Fig. 8.

The green-magenta axis is clearly a 'preferred direction' for errors due to differential gamma mismatch; this is most noticeable in the case of the low luminance skin colours (nos. 20, 21 and 22); hence one would expect difficulties with shadows on faces: this is indeed a problem in studio practice.

It remains to adjust the mathematical treatment to allow for the true display-tube gamma of 2·8. The skin-tone reproduction of Fig. 9 are produced for this case, showing an increase in the general green-magenta errors. As far as skin tones are concerned, errors in the green channel gamma corrector apparently tend to override those in the red or blue channels.

4. Discussion and conclusions

Section 2 has showed that objectively accurate colorimetry can only be approached when the television system has a linear overall transfer characteristic. In order to satisfy this condition the camera gamma-correctors would require substantial improvement; at present correction is carried out according to a law of exponent 1/2·2 instead of 1/2·8 which results in an overall gamma of 1·273 instead of unity. The resulting pictures are usually regarded as pleasing and satisfactory and there may well be an argument in favour of departing from strict overall linearity so that the television picture is a little 'larger than life' in terms of saturation. However, this point of view has not been firmly established and it would certainly be of interest to test a complete colour television chain with an overall linear transfer characteristic; this clearly would involve a gamma corrector to an exponent of 1/2·8. This report is confined mainly to objective colorimetric-analysis and it is not possible to be very explicit on the subjective appreciation of the colour picture.

Section 3 showed how the performance of practical gamma-correctors falls short of that of true power-law gamma correctors, particularly at low luminances. For skin tones, a preferential error direction for differential mismatching of gamma-corrector characteristics is shown to lie along the green-magenta axis. This provides a possible explanation for the presence of disturbing green or magenta shadows on faces in camera pictures and underlines the critical importance of being able to match the gamma-correctors at their low signal levels. Since the gamma-corrector errors treated here lie within the limits detectable on present waveform monitors, it is suggested that the matching of gamma characteristics may not at present be accurate enough.

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